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Unipolar semiconductor lasers on asymmetric quantum wells

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Abstract. We propose the original design of an active element of quantum unipolar semiconductor laser both for the optical pumping and current injection modes of operation. The peculiarities of the proposed design are strongly asymmetric barriers surrounding a double-well active element. The suppression of intersubband transitions to the lower working subband can be readily achieved if the transformation point of electronic state dimensionality for the lower subband occurs at small momentum. By this means the population inversion conditions in this system can be easily realized. The results of photoluminescence studies of the individual elements of the proposed structure are presented.

Theory

The double QW structure with asymmetric barriers, which permits to suppress sufficiently the intersubband relaxation, was proposed by us earlier [1]. The design of this structure facilitates the achievement of the intersubband population inversion and consequently the reduction of the threshold pump currents and pumping intensity respectively in the current injection [2] and fountain [3] modes of operation. In this case, the situation of both coherent photonic and electronic subsystems is possible as well as lasing even without the population inversion [4].

The asymmetry of the barriers causes an existence of 2D subband of the corresponding QW only in restricted region of 2D wave vector $0 < |\mathbf{k}| < k_c$ because of 2D–3D transformation of electronic state dimensionality. The intersubband relaxation is appreciably suppressed if the distance between the 2D–3D transformation point k_c of the lower subband and bottom of the upper subband exceeds the LO phonon energy E_{LO} . We propose here the original design of an active element both for the optical pumping and current injection modes of operation. In Figure 1, the band diagram of the laser structure with optical pumping is shown.

The active element comprises two QW of h_1 and h_2 width separated by narrow barrier. We use the scheme with pumping between ε_1 and ε_3 subbands and lasing between ε_3 and ε_2 subbands. The peculiarity of the proposed design is the insertion of this active element between the asymmetric barriers U_0 and U_1 ($U_1 \ll U_0$) where U_1 lies close to the ε_2 subband. With such an active element, the transformation of electronic state dimensionality for ε_2 subband allows to increase appreciably the phonon relaxation time τ_{32} and strengthens the inequality $\tau_{32} \gg \tau_{21}$. The latter is necessary for the population inversion achievement.

Taking into account the finite width L of U_1 barrier in the real structure, the active element design was optimized on the basis of calculations of phonon intersubband relaxation times τ_{ij} and dipole matrix elements z_{ij} ($i, j = 1, 2, 3$). The concrete calculations were performed for the structure on the basis of GaAs/AlGaAs system with a molar fraction of Al in the right barrier $x = 0.35$ and that of U_1 barrier $x \sim 0.09$. The QW widths in the active region ($h_1 = 82 \text{ \AA}$, $h_2 = 51 \text{ \AA}$) were chosen to obtain the energy gap between

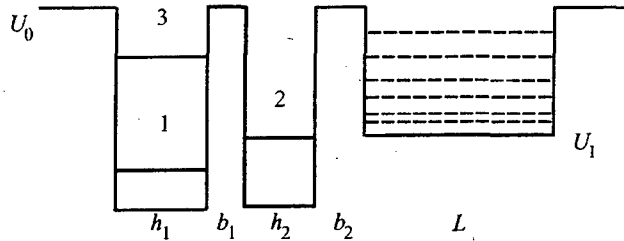


Fig. 1. Band diagram and position of size-quantization levels.

ε_3 and ε_1 subbands of the order of 120 meV (for pumping with a CO₂ laser), and $\varepsilon_2 - \varepsilon_1$ separation close to E_{LO} ($E_{LO} \approx 36$ meV). In this case, τ_{21} takes a minimum and reaches 0.5 ps. The width of separating barrier b_1 was chosen to optimize a $\eta = (\varepsilon_3 - \varepsilon_2)(z_{31}z_{32})^2$ value, which determined the ratio of the gain in the system to the loss [3]. The product $z_{31}z_{32}$ has a maximum at $b_1 \approx 14$ Å.

We have found that the insertion of a narrow barrier b_2 of U_0 height between h_2 QW and U_1 barrier allows one to improve the lasing characteristics. This barrier affects τ_{32} and τ_{21} values and permits to control z_{ij} values. The product $z_{31}z_{32}$ increases steadily with b_2 and at $b_2 = 20$ Å nearly coincides with that of the structure with symmetric barriers ($U_1 = U_0$).

One has to increase τ_{32} to obtain the population inversion. In the proposed design this is achieved as a result of the escape of electrons of ε_2 subband with a finite momentum of longitudinal motion to the region of low barrier U_1 . This effect occurs at a reasonable large L . In this case, a quasi-continuous (QC) spectrum is formed in this region and the additional mechanism of the electron escape from the upper laser subband ε_3 appears. Moreover, with appropriate choice of L the escape of the electrons from ε_3 subband to the states of the QC spectrum formed over U_1 barrier appears to be suppressed. The described approach allows one to refuse complex injector design in the form of graded Bragg superlattice for quantum cascade laser [2] and simplifies a change-over from the optical pumping to the injection mode of operation.

We carried out numerical calculations of the b_2 dependences of the relaxation times τ_{31} and τ_{32} for intersubband transitions with a participation of optical phonons, the escape time of electrons from the upper subband to the region of QC spectrum τ_{3con} , and the total lifetime τ_{3tot} for the ε_3 subband at $L = 400$ Å and $U_1 = 81$ meV. There is a flat maximum of τ_{3con} at $b_2 \sim 30$ Å. As this takes place, the total lifetime τ_{3tot} is close to its limiting value, and $\tau_{32} \approx 4$ ps being 2.7 times as much as that for the structure with symmetric barriers.

Figure 2 shows the dependences of the relaxation times on the width L of the region forming a QC spectrum. The maxima τ_{31} and minima τ_{3con} , τ_{3tot} at $L \approx 340$ and 420 Å are due to the appearance of the level, which is in resonance with ε_3 , in the region of QC spectrum. In this case, the wave function of ε_3 state penetrates significantly in the region of low barrier L , causing the decrease in the overlap with wave functions of ε_1 and ε_2 states and the increase in the overlap with states of QC spectrum. The abrupt change of τ_{3con} at $L = 350$ Å is associated with the approach of the next level of the QC spectrum to the ε_3 level by a distance equal to E_{LO} energy. Thus, the optimal value of L lies in the region of 400 Å.

In order to optimize the laser on the population inversion I parameter, we wrote equations that describe non-equilibrium kinetic processes in the structure under study. It was shown that the dependence $I(L)$ keeps a strong non-monotonous character owing to the

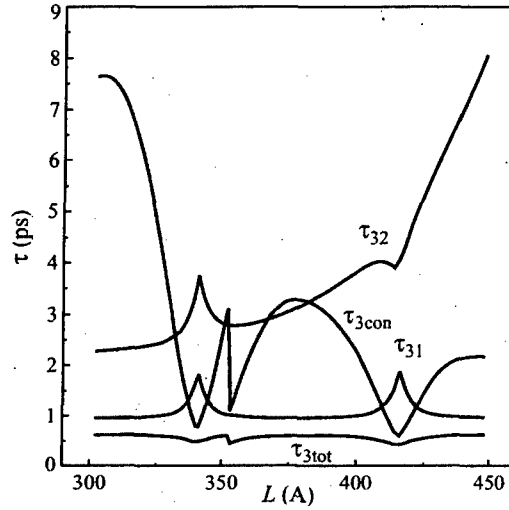


Fig. 2. Dependences of the relaxation times on the width L of the region forming a QC spectrum.

sharp modulation of relaxation rates with L for the various subbands.

The presence of QC subbands decreases the value of population inversion. For example, when a single QC subband ε_0 exists, the population inversion is expressed by the equation

$$I = \frac{\tau_{32}}{\tau_{21}} \left(1 + \frac{\tau_{32}}{\tau_{30}} \frac{\tau_0}{\tau_{02}} \right)^{-1}, \quad (1)$$

where τ_{ij} is the electron relaxation time from ε_i subband to ε_j one and τ_0 is a full lifetime in ε_0 subband. Obviously, the top limit of equation (1) is reached, when $\tau_{30} \gg \tau_{32}$ and $\tau_{02} \gg \tau_0$. However, not all the QC subbands participate effectively in electron relaxation from the ε_3 subband to ε_2 one. The transitions to QC subbands separated from ε_3 subband with a gap smaller than E_{LO} are forbidden by the law of energy conservation. If the intersubband relaxation time exceeds the intrasubband time, the electrons are accumulated near the subband edges. In this case, the transitions to the ε_2 subband from the QC subbands separated with a gap smaller than E_{LO} are also prohibited. On these grounds, it is possible to suppress significantly the influence of the QC spectrum on the population inversion.

Experimental results

To study the concurrence of the mechanisms of interband radiative recombination and tunneling through the narrow barrier, the photoluminescence (PL) was measured of single QW with symmetric barriers one of them having the width that was varied in the range $d = 3-10$ nm. The unipolar regime under consideration is realized when the tunneling time appears to be lower than the recombination time. It should be stressed that the tunneling time in its turn determines the intersubband relaxation time. When narrowing barrier the possibility to alter the lifetime of coupled electronic state in a broad range was demonstrated. The variation of lifetime between two limiting cases when it was determined by tunneling from QW through the barrier ($d = 40$ Å) and by radiative recombination time ($d = 80$ Å) was realized. It was found that 80 Å barrier effectively prevents tunneling. The intensity of QW peak drastically decreases for the structure with 60 Å barrier. This is an evidence of the key role of the tunneling through 60 Å barrier in this structure. There is no QW

contribution in the PL spectrum of the structure with 40 Å barrier and tunneling through the narrow barrier dominates.

The drastic modification of the degree of electronic-wave-function localization in 2D–3D transformation point was demonstrated from comparison of PL spectra of 40 Å GaAs/AlGaAs single QW with strongly asymmetric barriers and of the similar structures but with the additional wider (60 or 80 Å) QW with symmetric barriers coupled with the initial one. The latter structure is a component of the active element of a fountain laser. We have shown that this structure permits one to increase considerably the degree of electronic wave function localization in QW at $k = 0$ that determines the oscillator strength of the working laser transition with only minor variation of the critical value of wave vector of 2D–3D transformation.

The key feature of the proposed scheme is the resonance of the lower subbands in the asymmetric and symmetric QW. This is achieved by the increase of the width of QW with symmetric barriers. For the structure with 60 Å QW the ground subband of this well is sufficiently higher than the ground subband in asymmetric QW and the resonance and thus the transformation point in this subband are absent. Therefore, the transition to this subband from higher states is not suppressed and the ground subband in symmetric QW is highly populated. This is the reason of high intensity of QW peak. For the structure with 80 Å QW the ground state in the symmetric QW appears to be at lower energy and in resonance with the ground subband in asymmetric well. For this reason the ground subband in this structure has the transformation point and the transitions to this subband are suppressed. That is why the intensity of QW peak for this structure is sufficiently weaker. For the structure with single asymmetric QW the discussed effect is weaker due to the lower degree of localization of electronic wave function.

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References

- [1] V. F. Elesin, A. V. Tsukanov, V. V. Kapaev and Yu. V. Kopaev, *JETP Lett.* **66**, 742 (1997).
- [2] J. Faist, F. Capasso, D. Sivco, C. Sirtori, A. L. Hutchinson, S. N. G. Chu and A. Y. Cho, *Science* **264**, 553 (1994).
- [3] O. Gauthier-Lafaye, S. Sauvage, P. Boucard, F. H. Julien, F. Glotin, R. Prazeres, J.-M. Ortega, V. Thierry-Mieg and R. Planel, *J. Appl. Phys.* **83**, 2920 (1998).
- [4] V. F. Elesin, *JETP* **85**, 264 (1997).